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RESULTS OF EVAPORATION STUDIES
CONDUCTED AT THE
SCRIPPS INSTITUTION OF OCEANOGRAPHY
AND THE
CALIFORNIA INSTITUTE OF TECHNOLOGY

BY
GEORGE F. MCEWEN

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INTRODUCTION

This is a summary of investigations which have been published in detail in several different series. It was prepared in order to make readily available in one paper the essential results of a unified attack upon the general problem of evaporation. All of the results are comparatively recent and have never before been presented in one publication.

Although complementary to precipitation and of equal importance, there is much less quantitative information about the rate of evapor-

ation than about precipitation. This is due to the fact that while the measurement of precipitation is direct and readily made, evaporation must be determined indirectly from suitably made observations. For example, direct observations from a pan must be corrected by special methods in order to obtain the evaporation from a neighboring lake or reservoir. Although many investigators have worked on the problem of determining the rate of evaporation from lakes and reservoirs, discordant results have been reached, owing to inherent difficulties and to lack of time for carrying out a thorough rational investigation of suitable technic. Empirical methods have been used and there has been no general agreement regarding either the relation of pan evaporation to that of a large body of water or the method of estimating it from meteorological data. Even less satisfactory information has been obtained about ocean evaporation, owing not only to certain observational difficulties not met with on land, but also to lack of a rational method of interpreting the observations. Available observations indicate a rate of about 2.7 feet per year from the sea. There is also evaporation from the soil which under different conditions varies from about 20 per cent to 90 per cent of that from a water surface.

About fifteen years ago at the Scripps Institution, while working on problems of circulation and temperature distribution I was handicapped by this meager knowledge of ocean evaporation (McEwen, 1919, pp. 340 and 413). The available results of evaporation investigations were either purely empirical and therefore of only local value, or theoretical but involving simplifying assumptions departing so widely from actual conditions in nature, that the general conclusions could not be accepted. Even combinations of existing theoretical and empirical methods that proved very helpful in certain local engineering problems of water supply, lacked the desired quality of being generally applicable.

In spite of the need of a clear understanding of the physics of evaporation long recognized by engineers, geologists, meteorologists, and oceanographers, no investigation of the subject, leading to satisfactory results, had been carried out up to that time. Mr. Cummings, then assistant in physical oceanography at the Scripps Institution, undertook, at my suggestion, to make a critical study of the problem of evaporation. This investigation begun at the Scripps Institution led to cooperative work at the California Institute of Technology a few years later by Messrs. Cummings, Bowen, Richardson, and Montgomery, to whom I am indebted for material condensed into the following summary.

EVAPORATION STUDIED FROM THE STANDPOINT OF TRANSFORMATIONS OF ENERGY

It is natural to regard evaporation from lakes as a process controlled by atmospheric conditions, such as air temperature, wind, and humidity. This view, then shared by Mr. Cummings, was not supported by an extensive statistical analysis which he made for the purpose of isolating the effects of various factors influencing evaporation. In particular, a very weak correlation was indicated between evaporation and humidity. He concluded that there must be a fundamental physical reason for this unexpected result.

Accordingly, it was decided to make a new beginning and attack the evaporation problem from the standpoint of the first law of thermodynamics. This investigation led him to formulate the following qualitative principle of evaporation analogous to the principle of Le Chatelier, in physical chemistry, and Lentz's law in electricity and magnetism (Cummings, 1929, p. 49). Any change in wind or humidity is always accompanied by a change in lake temperature which partially neutralizes the direct effect on the evaporation rate to be expected from the original change in atmospheric conditions, if the insolation remains constant.

The evaporation rate must evidently be determined entirely by energy, rendered available for that purpose in accordance with the equation

$$E = \frac{I - B - S - K - C}{L} \quad (1)$$

where (E) is the evaporation rate expressed in centimeters of depth, (I) is the incoming radiation per cm^2 of surface, (B) is the back radiation to the sky, (S) is the heat consumed in warming the water (or heat storage), (K) is a correction due to heat transferred to or from the air as sensible heat, (C) is a combined correction for leakage through the walls of the container, expansion of the water, and heat carried by flowing water, and (L) is the latent heat of vaporization of water (Cummings, 1929, p. 50). All quantities in the numerator are expressed in gram calories per square centimeter of open water surface and integrated or summed over the time interval corresponding to (E). Let (R) be the ratio of sensible heat carried away by the wind and diffusing into the air to the latent heat carried off by the vapor. Then

$$LER = K \quad (2)$$

The ratio (R), although generally regarded as small, is not negligible, but available information was crude and limited. Thus the approximate equation used by Cummings (1929, p. 51) to estimate evaporation from lakes

$$E = \frac{I - B - S - C}{L(1 + R)} \quad (3)$$

where (R) was regarded as a correction to be determined empirically, suggested the need of a critical investigation of its value.

THEORETICAL DETERMINATION OF THE BOWEN RATIO, R , OF THE LOSSES OF SENSIBLE TO LATENT HEAT

An attempt to obtain a theoretical relation of the value of (R) to easily measurable quantities, and thus make possible an accurate estimate of evaporation from equation (3) was successfully carried out by I. S. Bowen at the California Institute of Technology. For simplicity Bowen (1926) at first assumes diffusion coefficients, conductivities, and densities to be independent of temperature.

Then

$$m = \frac{D_1 a (\rho_1 - \rho_2)}{l} \quad (4)$$

is the mass of water vapor diffusing per unit time across a space of length (l), and area (a), where (ρ_1) and (ρ_2) are densities of water vapor at the two faces of the space, and (D_1) is the diffusion coefficient of water vapor through the air. Multiply both sides of equation (4) by (L), the latent heat of vaporization and denote the energy per unit volume in the form of latent heat by (θ_1) and (θ_2), the energy (Lm) carried across becomes

$$Lm = \frac{D_1 a (L\rho_1 - L\rho_2)}{l} = Q_L = \frac{D_1 a (\theta_1 - \theta_2)}{l} \quad (5)$$

The formula for heat energy (Q_s) carried by conduction across the same space is

$$Q_s = \frac{Ca(T_1 - T_2)}{l} \quad (6)$$

where (C) is the conductivity of the air, and (T_1) and (T_2) are the temperatures of the two faces. But

$$C = D_2 C_p d \quad (7)$$

Where (D_2) is the "diffusion coefficient" or diffusivity for the heat energy, (C_p) is the specific heat at constant pressure, and (d) is the density of the air. Therefore the substitution of this value of (C) in (6) results in the equation

$$Q = \frac{D_2 a (\phi_1 - \phi_2)}{l} \quad (8)$$

where $\phi_1 = T_1 C_p d$ and $\phi_2 = T_2 C_p d$ are respectively the densities of specific heat energy at the two faces. The equations (5) and (8) for the transfer of latent and sensible heat respectively are of the same form, and from kinetic theory (D_1) is only a few per cent greater than (D_2). Accordingly, heat losses by evaporation, diffusion, and conduction should follow the same laws and be affected in the same way by convection.

CASE I—

Suppose first, that the wind velocity has a constant value from the surface to a small height, (b), above the lake surface. If the lake is large and the velocity and height (b) are small, the layer of air from (o) to (b) will have its temperature changed to that of the water and will become saturated with water vapor. That is, its specific heat density will change from (ϕ_2) (value at windward side) to (ϕ_1) (value at water surface), and similarly its latent heat density will change from (θ_2) to (θ_1).

Therefore

$$R = \frac{\phi_1 - \phi_2}{\theta_1 - \theta_2} \quad (9)$$

since this is the ratio of the two kinds of energy taken on by each cubic centimeter of the air passing over the lake.

CASE II—

Suppose there is no wind between the lake surface and the height (b). If the area of the lake is small and the velocity large, the water vapor and heat diffusing through the stationary layer from the lake surface to the height (b) will be carried away immediately and we can assume ($\phi = \phi_2$) and ($\theta = \theta_2$) at the layer at height (b). Under these conditions the rates at which heat and water vapor leave the water surface are determined solely by diffusion, and their ratio, found by dividing equation (8) by (5) is

$$R = \frac{D_2}{D_1} \left[\frac{\phi_1 - \phi_2}{\theta_1 - \theta_2} \right] \quad (10)$$

Case I represents a condition where the whole quantity of air under consideration is completely changed in temperature and moisture content to that of the layer of air in contact with the water. For this reason diffusion is not the limiting factor and hence the diffusion coefficients do not enter into the formula for the ratio of the heats lost by the two processes. It is obvious, however, that if conditions are such that diffusion does enter it will be in such a way as to increase the loss by the process having the larger diffusion coefficient relative to the loss by the other method. Hence under any condition of wind we may say, since $D_1 > D_2$ that

$$R \leq \frac{(\phi_1 - \phi_2)}{(\theta_1 - \theta_2)} \quad (11)$$

Case II, on the other hand, represents conditions where diffusion is the completely determining factor, the heat and water vapor being immediately carried away after diffusing through the stationary layer. If, however, they are not immediately carried away, they tend to build up the temperature and vapor density on the upper side of this layer, and thus decrease the gradient in the stationary layer. This in turn tends to slow down further diffusion. But the process with the larger diffusion coefficient will build up faster, and hence will be retarded more than the one with the lower diffusion coefficient. Hence we can write

$$R \geq \frac{D_2(\phi_1 - \phi_2)}{D_1(\theta_1 - \theta_2)} \quad (12)$$

Also, a pair of differential equations derived from the basic assumptions, and valid for all points above a lake, was solved, assuming the wind velocity to be proportional to any positive power (a) of the distance above the surface. This led to the results

$$R = \frac{Q_s}{Q_L} = \left(\frac{D_2}{D_1} \right)^{\frac{n+1}{n+2}} \left(\frac{\phi_1 - \phi_2}{\theta_1 - \theta_2} \right) \quad (13)$$

Making use of well known relations of (D_1), (C), and (D_2) to temperature, Bowen found that equations (9) and (10) reduced respectively to

$$R = .501 \left(\frac{T_w - T_a}{P_w - P_a} \right) \frac{P}{760} \quad (14)$$

and

$$R = .442 \left(\frac{T_w - T_a}{P_w - P_a} \right) \frac{P}{760} \quad (15)$$

which he replaced by

$$R = .46 \left(\frac{T_w - T_a}{P_w - P_a} \right) \frac{P}{760} \quad (16)$$

since the general solution indicates that, under ordinary conditions the value of (R) is nearer to that given by equation (15) than by equation (14). In this equation

T_a = temperature of the air

T_w = temperature of the water

P = pressure of the air in mm

P_a = the partial pressure of water vapor in mm

P_w = the partial pressure of water vapor if the air were saturated and had the temperature of the water surface.

ALIGNMENT DIAGRAM FOR COMPUTING THE BOWEN RATIO, R

In order to facilitate the computation of the Bowen Ratio an alignment diagram has been prepared by Cummings (1930a).

A straight edge passing through a certain pair of points, determined by any particular set of data, cuts a straight line which is so graduated that the value of R can be read off directly. The first of these points is the intersection of the line corresponding to the given dry bulb temperature with that corresponding to the wet bulb temperature, and the second point lies on a slightly curved line and corresponds to the given water temperature. Experience has shown that R can be determined in this way with an error of about one one-hundredth.

THEORETICAL LIMITS OF THE RATIO OF ACTUAL EVAPORATION TO EVAPORATING POWER OF INCIDENT RADIATION

By means of the alignment diagram it can be shown (Cummings, 1930b) that the actual evaporation from a water body must lie between 42 per cent and 100 per cent of the evaporating power¹ of the radiation falling on the body. These limits have been set far enough apart to take account of the greatest ranges of conditions that can possibly occur. The ranges of variation that do occur with sufficient frequency to be important from the standpoint of practical hydrology are much smaller than these extremes.

¹ This term is used by McEwen to denote the depth of water that would evaporate if all the incident radiant energy were converted into latent heat.

EXPERIMENTS MADE TO TEST BOWEN'S THEORETICAL VALUE OF THE RATIO R

Bowen's theory, relating (R) to readily measurable quantities, thus provides the information needed to render Cumming's equation (3) exact. However, the importance of being able to estimate (R) renders the independent tests of Bowen's theory highly desirable. In order to establish its validity and discover its limitations, Cummings and Richardson (1927) undertook to test the theory by experiments involving the comparison between a small insulated evaporating pan and large tanks.

Solving equation (3) for ($I - B$) results in

$$H = I - B = S + LE(1 + R) + C \quad (17)$$

where (H) is called the heat budget per square centimeter of surface. (I) must be the same for all water surfaces exposed to the same external conditions, but (B) varies with the surface temperature, and is therefore in general different for different bodies of water. Using subscripts (₁) and (₂) for the pan and the other bodies of water respectively, and remembering the equality of (I_1) and (I_2) results in the equation

$$B_1 - B_2 + S_1 + LE_1(1 + R_1) + C_1 = S_2 + LE_2(1 + R_2) + C_2 \quad (18)$$

The difference in temperature found between the two water surfaces being less than 15° C in his experiments, Stefan's law of black body radiation gives ($T_1 - T_2$) (.5) as the value of ($B_1 - B_2$) in calories per sq. cm. per hour. Therefore, since all quantities in equation (3) can be directly measured, it can serve to test Bowen's theory under any desired conditions. Moreover, if the theory is correct, and the evaporation (E_2) from one body, a lake for example, can not be measured equation (18) can be used to compute it.

DIMENSIONS OF CONTAINERS USED FOR TESTING
BOWEN'S THEORY

	Pan	Tank, Pasadena	Tank at Fort Collins, Colorado
Area	0.37	2.2	520. square meters
Depth of vessel	0.19	1.47	2.0 meters
Depth of water below rim	.01	.02	.07 meters

The tank at Fort Collins was so large that insulation was unnecessary. Both of the other containers were insulated and corrections were made for the small leakage. Many comparative runs were made under quite dissimilar circumstances. A remarkably close agreement was found between the two members of equation (18), thus proving Bowen's method of determining (*R*) to be of high precision under field conditions. Therefore the evaporation from a lake can be computed by determining (*H*₁) from pan observations near the lake and applying the (*B*₁ — *B*) correction for estimating *H* = *I* — *B*, the heat budget of the lake and substituting in the equation

$$E = \frac{(H - S - C)}{L(1 + R)} \tag{19}$$

where (*S*), (*R*), and (*C*) are determined for the lake.

This research is more than a comparison of evaporation from two containers of different dimensions, since if any technique is ever developed for measuring (*H*), then lake evaporation can be found without using a pan or measuring wind velocity. The procedure outlined can be used to measure lake evaporation with satisfactory precision and reliability, and although, like most primary standards it is difficult to apply, it should aid in developing methods more readily applicable, in case great accuracy is not required.

Before this investigation empirical estimates of lake evaporation based upon pan observations were subject to error since water in pans of different sizes is known to evaporate at different rates. There was no general agreement as to the proper method of reducing pan evaporation to lake evaporation.

Evidently it is important to make many field tests of the value of (*R*) under dissimilar conditions, and thus provide general information regarding the probable value of this correction.

This procedure measures by means of a pan, the amount of energy available for dissipation by the larger body of water in the items of evaporation convection, and sensible heat, but does not enable the absolute amount of energy reaching the water surface to be computed. Only the back radiation difference between the pan and tank has thus been considered.

RADIATION-EXCHANGE BETWEEN WATER AND AIR AND THE MEASUREMENT OF INSOLATION

A later detailed consideration by Richardson and Montgomery (1929) of the radiation-exchange between the water and the atmosphere indicated that the effective radiation from a water surface could be accurately represented by the equation

$$B = aT_w^4 - baT_a^4 \quad (20)$$

where (T_w) and (T_a) are respectively the absolute temperature of the water and the air above it, (b) is a factor (approximately equal to .9) which corrects for the fact that the atmosphere does not radiate as a perfectly black body, and (a) is Stefan's constant. From results of later studies Richardson (1930) determined two correction factors to apply to this equation. The first term is multiplied by the factor .906 to correct for the fact that water does not radiate as a black body. Since air does not radiate as a black body and the temperature used is that of air directly above the water instead of the sky to which the energy radiates the second term is multiplied by the correction factor .790. These changes remove a slight inconsistency with results obtained by Schmidt and put the formula on a more rational basis, although no significant change is thereby made in the numerical result. Accordingly the incoming radiation from the sun and sky per square centimeter of surface, corrected for reflection, can be computed from pan observations from the equation

$$I = S + LE(1 + R) + B + C \quad (21)$$

Comparisons of values of (I) computed from this equation with pyrheliometer readings indicated a departure of but 4 per cent. Accordingly the evaporation from an exposed body of water computed from the equation

$$E = \{I - .906 aT_w^4 + .790 baT_a^4\} \div L(1 + R) \quad (22)$$

(using the modification of equation 20) will be subjected to a small relative error of about 4 per cent where either pan or pyrheliometric observations are used for estimating the available solar and sky radiation denoted by (I) . Richardson's (1930) computations of the amount of evaporation from forty bodies of water by this energy formula (22) agree very well with results obtained by other methods.

During the progress of these investigations which, except for observations of the total amount of heat in the body of water, were concerned with conditions in the air above the water surface, I was attacking the problem from a different angle. However, all of these investigations were based upon energy changes.

EVAPORATION COMPUTED FROM VERTICAL GRADIENTS IN WATER OF TEMPERATURE AND SALINITY

Oceanic circulation involving a general flow either vertical or horizontal causes corresponding changes in the distribution of temperature and salinity. For example, investigations of the California coastal region indicated marked changes of this kind (McEwen, 1912, 1927). In attempting to work out quantitative relations between circulation and the accompanying temperature changes it was found necessary to determine the "normal" distribution of temperature and salinity. That is, it became necessary to develop a physical theory of the absorption of solar radiation, back radiation from the surface, conduction of heat through the air, heat loss due to surface evaporation, and the transfer of heat and other properties of the water by the alternating motion of water, especially from one level to another.

This general problem pertains not only to the ocean but to all exposed bodies of water. My treatment (McEwen, 1929) of it assumes that the time rate of change of temperature at any given level in a lake may be regarded as an effect of four groups of causes.

First, the water is heated directly by the absorption of solar radiation. This direct heating is negligible below the upper few meters, within which nearly all of the energy of the incident radiation is absorbed.

Second, heat is transferred within the lake from one level to another, by means of eddy motion or turbulence in a manner agreeing, formally, with the law of heat conduction in solids.

Third, because of winds or horizontal gradients of specific gravity there may be a general drift or flow of the water, resulting in an accompanying transfer of heat.

Fourth, heat is removed from the water surface by evaporation, back radiation, and conduction through the air. The resulting increase of specific gravity of a thin surface layer of the water causes a settling of relatively heavy and cool masses of surface water, compensated by a rise of relatively warm and lighter water.

All but the fourth group of causes have been extensively investigated, and a theory of this diffusion of surface heat loss downward can be developed as follows:

Assume that surface water masses tend to remain at that level, and consequently do not descend unless adequate forces are present. General experience relative to the variability of conditions in open bodies of water, such as lakes, suggests that at different positions on the surface the forces required to cause the water masses to descend will be different. Accordingly in the absence of detailed knowledge a

normal frequency distribution of density departures is assumed, and the rate of settling of each small water mass at any level is assumed to be proportional to the difference between its specific gravity and that of the surrounding water. Thus water masses whose specific gravity and corresponding temperature vary through a certain range fall to different levels, and the surrounding water rises. Furthermore continuity of mass requires an equality of upward and downward flow at each level.

Using this basis the problem was formulated by attempting to devise a mechanism whose behavior could be worked out mathematically. By a process of fitting the resulting equations to observations of temperature and salinity from the surface to a depth not exceeding 100 meters even in the ocean, and repeated at regular time intervals, the physical constants can be computed corresponding to each time interval. These computations furnish theoretical estimates of the rate at which solar radiation penetrates the surface and the rate of surface cooling. Thus, by applying the Bowen ratio and back radiation correction used by Cummings and Richardson, an estimate of evaporation is provided without the use of the pan. Furthermore, by applying the same mechanism of downward diffusion to the distribution of salinity and combining the resulting equations with those pertaining to temperature a method has been worked out for estimating separately the surface cooling due to evaporation and to other causes. This method is independent of all observations except serial temperatures and salinities and is theoretically adequate for estimating evaporation from the ocean (McEwen, 1929).

THE BEARING OF LAPSE RATES UPON THE QUESTION OF USING OBSERVATIONS MADE AT DIFFERENT HEIGHTS ABOVE THE WATER SURFACE

In general it is impracticable to observe the air temperature, wind, and humidity at the water surface. At sea such observations are usually made at a height of many feet above the water surface. The time rate at which water vapor diffuses upward from the water surface depends upon the water temperature, the temperature and humidity of the air, and the wind velocity at that level. Attempts to reduce the observations to values corresponding to a common level by means of Dalton's equation have not yielded satisfactory results. Although this point of view is undoubtedly sound at least qualitatively, the difficulties of its practical application appear insurmountable.

The point of view that the quantity of water evaporated during any time interval is determined entirely by energy considerations, as

explained by Cummings and Richardson (1927), has been shown to be theoretically sound. Moreover, this energy basis can be applied in practice to determine the evaporation from large bodies of water.

An extended series of measurements of evaporation and observations of atmospheric conditions at three levels from the sea surface up to a height of fifty feet at the end of the Scripps Institution's pier during the summer of 1928 indicated very small vertical gradients. For practical purposes observations made at any level from the surface to the fifty-foot level can be used interchangeably. Values of the radiation computed from observations of evaporation, water temperature, air temperature, and humidity at each of the three evaporating pans agreed well with the observed values at the upper level. In fact, the results confirmed previous conclusions (Cummings and Richardson, 1927; Richardson and Montgomery, 1929; and Richardson, 1930). That is, according to these experiments lapse rates do not interfere with the determination of evaporation from observations made at various levels in the atmosphere if the energy basis is used.

DIRECT EXPERIMENTAL DETERMINATION OF RELATION OF EVAPORATION TO ATMOSPHERIC CONDITIONS AND SIZE OF PAN

Dr. Cummings is conducting experiments for the purpose of determining in a statistical way the relation between atmospheric conditions and rate of evaporation from a water surface exposed to the sun and sky. In order to make the results applicable to lakes, he uses thermally insulated vessels.

Since the rate of exchange of sensible heat energy between the atmosphere and a water surface is seldom as much as 25 per cent of the evaporation for a period as great as twenty-four hours, it is to be expected that such changes as ordinarily occur in atmospheric conditions will not produce changes in evaporation which are large in comparison with the total evaporation. In other words, there is no reason to expect a large coefficient of correlation between evaporation and humidity or between evaporation and wind. On the other hand, a very strong correlation is to be expected between evaporation and insolation as measured by a pyrheliometer.

Moreover, the size of the evaporating surface should have very little effect when the vessels are thermally insulated although it is known to have a marked effect when the vessels are not insulated. Experiments thus far made confirm these deductions, and the results will be published in detail by Dr. Cummings.

CONCLUSION

This paper presents a review of certain recent investigations of phenomena occurring in the zone of contact between air and water with particular reference to the problem of determining evaporation from large, exposed bodies of water. The energy basis for these studies has been proved to be sound and has resulted in satisfactory standard procedures for determining evaporation to within the small error of 3 per cent. Such a result is essential in the development and testing of empirical methods of less precision that can be more readily applied in practice where an error of as much as 10 per cent is often permissible. Moreover, satisfactory progress has been made in developing these simpler methods without undue loss of accuracy.

The general investigation involved observations on fresh water lakes and even on small containers under conditions approaching those of laboratory experiments. Yet throughout the work the field problem of determining evaporation from the sea was kept in mind. In fact, this investigation illustrates the need of approaching problems in oceanography by means of both laboratory and field work.

The rather large amount of time and effort devoted to the subject of evaporation is fully justified by its importance in the fundamental worldwide phenomena of the water cycle between the land, ocean, and other water surfaces.

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